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Business Models for Additive Manufacturing: Exploring Digital Technologies, Consumer Roles, and Supply Chains

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ABSTRACT

Digital fabrication—including additive manufacturing (AM), rapid prototyping and 3D printing—has the potential to revolutionize the way in which products are produced and delivered to the customer. Therefore, it challenges companies to reinvent their business model—describing the logic of creating and capturing value. In this paper, we explore the implications that AM technologies have for manufacturing systems in the new business models that they enable. In particular, we consider how a consumer goods manufacturer can organize the operations of a more open business model when moving from a manufacturer-centric to a consumer-centric value logic. A major shift includes a move from centralized to decentralized supply chains, where consumer goods manufacturers can implement a “hybrid” approach with a focus on localization and accessibility or develop a fully personalized model where the consumer effectively takes over the productive activities of the manufacturer. We discuss some of the main implications for research and practice of consumer-centric business models and the changing decoupling point in consumer goods’ manufacturing supply chains.

KEYWORDS

3D printing; additive manufacturing; business models; digital fabrication; glocalized production; rapid manufacturing; rapid prototyping; supply chains

INTRODUCTION

Additive manufacturing (AM), which is also known as rapid manufacturing or 3D printing, has emerged as a new and disruptive manufacturing technology that has major implications for companies and industries at large (Phaal et al., 2011). Given that the AM industry is currently assessed at more than \$3 billion, with an expected rise to \$13 billion by 2018 and \$21 billion by 2020 (Wohlers, 2014), AM technologies have an enormous potential, although they also imply important and necessary changes to companies' business models—their logic of creating and capturing value (Afuah, 2014; Zott et al., 2011). As a hyper-flexible technology that can provide highly customized and personalized products and production, AM provides a specific set of opportunities and challenges for developing new business models (Piller et al., 2015; Ponfoort et al., 2014). In this paper, we analyze the recent advances in AM technologies and we explore their implications for business models in the consumer goods manufacturing industry, where they have a big potential to revolutionize the way products are produced (Berman, 2012; Gibson et al., 2010; Huang et al., 2013; Tuck et al., 2007).

Manufacturers of customized products in domains as dental, bio-medical, fashion and apparel have so far successfully adopted AM technologies. The hyper flexibility of AM technologies allows for customized shapes, digital interaction with consumers and direct manufacturing, which gives benefits in terms of lower costs, reduced supply chain complexity and lead times, etc. However, despite the potential, many questions pertain, for example related to the justification for mass manufacturers of commodity products to use AM technologies, the types of business models that they would have to employ to capitalize on the flexibility that AM offers, and how these changes would affect their operations and supply chain structures. Accordingly, our research question is: How do emerging AM

technologies impact business model development and operations in consumer goods manufacturing?

In this paper, we explore the new possibilities and challenges that AM presents to consumer goods manufacturers' business models with a particular focus on the potential to open up to a higher degree of consumer involvement and on the associated implications for the organization of production activities. In particular, shifting productive activities from manufacturers to consumers challenges the centralized nature of production systems and thus calls for a decentralization of supply chains. We will present an inductive study that is based on the general developments within AM technologies in the context of the consumer goods manufacturing industry. Specifically, we will propose that AM technologies fundamentally change the role of the consumer in consumer goods manufacturers' business models with a particular implication being that supply chains are becoming more distributed and decentralized to enable more personalized production of consumer goods. Effectively, productive activities shift from the manufacturer to the consumer, which leads to a need to decentralize and decouple the organization of the manufacturer's supply chain to embrace the central role of the individual consumer in the value creation-capture process.

BACKGROUND

There is a diversity of perspectives on the business model concept in the literature, without a wide consensus regarding its precise conceptualization (Zott et al., 2011). In general, a company's business model describes its logic of creating and capturing value (Afuah, 2014; Osterwalder & Pigneur, 2010; Zott et al., 2011). The concept arose from the emergence of the Internet, the growth of emerging markets, and the appearance of postindustrial technologies (Zott et al., 2011). Consequently, the growth of e-businesses promoted the need for a value-capturing model as a reaction to the value potential that was

created (Afuah & Tucci, 2001). On a more detailed level, a business model refers to a system of interdependent activities within and across the organizational boundaries that enables the organization and its partners to create value and capture part of that value (Zott & Amit, 2010). Amit and Zott (2001) moreover present a specific framework that comprises efficiency, complementarities, lock-in, and novelty to determine the value creation logic. Given that activities within a business model can also take place across organizational boundaries, the business model determines the logic of purposively managed knowledge flows in open innovation (Chesbrough & Bogers, 2014). Open business models accordingly use the “division of innovation labor” to create greater value by leveraging more ideas, resources and other assets that are available outside of the companies’ boundaries (Chesbrough, 2006; Frankenberger et al., 2013; Vanhaverbeke & Chesbrough, 2014).

Recently, AM, a hyper-flexible technology that can provide highly customized and personalized products and production, provides a new set of opportunities for developing a new logic for creating and capturing value from such products and processes (cf. Piller et al., 2015; Ponfoort et al., 2014; Wohlers, 2013, 2014). These changes imply enormous challenges—not the least for incumbent manufacturers—addressing various aspects of traditional business models, such as the value proposition, cost structure and value chain (e.g. Afuah, 2014; Chesbrough & Rosenbloom, 2002; Osterwalder & Pigneur, 2010). Given that there are different AM technologies available in the market and that traditional manufacturing technologies are still widely used, manufacturing companies need to explore or experiment with new business models based on the emerging technologies (Brunswick et al., 2013; McGrath, 2010). These exploratory processes imply an important interaction between technology and business model innovation (cf. Baden-Fuller & Haefliger, 2013), while furthermore making the link to the organization of production, including supply chains (cf. Bogers et al., 2015; Johnson & Whang, 2002; Koren, 2010).

A NOTE ON RESEARCH DESIGN

The empirical base consists of the general developments in AM technologies, business models, and supply chains, although we also rely on the recent experience of a large internationally-oriented manufacturer within the plastic component industry. The company has been utilizing digital fabrication for the purpose of prototyping for more than 20 years, and it has recently been working toward the adaptation of AM as consumer goods manufacturing concept. While some of the observations and analyses in this paper are based on the company's experience, our ultimate objective is to present the general case of the consumer goods manufacturing industry.

Based on the original research that we conducted, with the above-mentioned empirical base, we engaged in an inductive study in which we built on our investigation of the state-of-the-art AM technologies to derive business models that could leverage the latent value of these technologies. In this iterative process, we identified particular characteristics of the business model that could be derived from considering both the general developments in the industry and the particular developments within the focal consumer goods manufacturer. Ultimately, this led to a specification of key business model design parameters and related implications for supply chains.

ADDITIVE MANUFACTURING: FROM PRODUCTION TECHNOLOGIES TO BUSINESS MODELS

Here, we describe the state of the art of AM technologies, starting with AM as a manufacturing concept, and then leading up to a description of how AM fundamentally changes the logic of how companies can create and capture value (i.e. business models).

An overview of additive manufacturing technologies

In this paper, we refer to AM as the utilization of additive technologies for the production of customer-specific consumer goods. In contrast to rapid prototyping—the use of additive technologies for the manufacturing of single or multiple prototypes—AM is in principle repeatable and scalable as a production process. AM technologies have existed since the beginning of the 1980s—initially mostly as a prototyping tool—and they have recently emerged as a viable manufacturing technology due to significant improvements in part quality, price and manufacturing process time. Principles such as “lean” and “just in time” can also be considered here in the context of full-scale small batch production, with a focus on the customer and creating value, with more or less waste (“muda”) (cf. Tuck et al., 2007).

In order to understand the different AM platforms and technologies, we conducted a detailed state-of-the-art¹ analysis of AM technologies.² We explored the different AM technologies’ characteristics, advantages and disadvantages, and their feasibility for consumer goods production. Table 1 presents the six leading technologies that we identified, while the Appendix A provides a more detailed overview of each technology, its method of operation, and its current main use.

Insert Table 1 about here

¹ The analysis was concluded in 2014, which is therefore the reference point for this analysis.

² We note that the technologies explored in this paper are polymer AM production technologies alone. Several technologies use metal as well for rapid tool manufacturing and general metal production, such as Selective Laser Melting (SLM) or Metal Selective Laser Sintering (MSLS). Other technologies use wax and ceramics as base materials. These technologies will not be explored in this paper as the focus (in the consumer goods manufacturer that serves as the empirical base) is plastic parts production for consumer goods.

The basic characteristics of these emerging AM technologies have important implications for consumer goods production systems. Based on our analysis, we identified a number of dimensions that we consider essential to assess the feasibility of each of the AM technologies (see Appendix B for a more detailed assessment).³ These dimensions are the components of production that must be satisfied for AM to be recognized as a feasible production concept. Table 2 shows a description of the dimensions as well as the results of the comparison of the different technologies based on these dimensions. In the table, a score of 5 represents high (i.e. optimal) results, while a score of 1 represents low (i.e. critical) results. Results are benchmarked to existing injection molding manufacturing capabilities and have been evaluated with the use of experts in AM production processes. While Appendix B provides a more detailed assessment of the AM technologies in consumer goods production systems, we will focus (below) on the overall assessment and subsequently present the implications for business models.

 Insert Table 2 about here

Additive manufacturing technologies' potential sources of value

As seen from Table 2 and Appendix B, none of the technologies obtain a maximum score (i.e. optimal performance for the focal consumer goods manufacturer). However, several technologies show more promise than others due to the inherent characteristics of their technologies. In this analysis, it is clear that FFF is the leading technology with its potential to be implemented as a manufacturing concept. However, advances in other

³ Our analysis is primarily based on the assessment of the potential of AM technologies for the large consumer goods manufacturer that serves as the empirical base in this paper, while it thereby, at least indirectly, also extends to a part of the consumer goods industry at large.

technologies, for example biocompatible materials in PJM and color technology for SLS, could change this assessment in the future and, as such, alter the relative ranking of any of these technologies.⁴ Although they show exceptional part accuracy, the characteristics of SLA and DLP's materials make these technologies as less favorable for consumer goods manufacturing. Zcorp was also deemed unfit for manufacturing and is considered a prototyping technology, at least based on the current assessment.

Based on our assessment, the more general advantage of AM as a manufacturing concept lies in a number of factors. First, AM is a mass-customization and personalization-enabling technology (Hague et al., 2003; Gibson et al., 2010). It is a free forming process that enables the manufacturing of almost unlimited geometries at once without special tools and equipment. Furthermore, AM makes it possible to manufacture various parts in the same batch (Gibson et al., 2010). This presents some implications for the potential of “mass customization” (Reeves et al., 2011; Tseng & Piller, 2003), while also supporting the decentralization and localization of production (Walter et al., 2004; Hadar & Bilberg, 2012). Due to their high flexibility, AM platforms can free form shapes without the use of conventional tooling and machining. Since the same machine can produce almost any given part in any given location, it allows companies to implement it in any of their locations, whether a production facility or even an inventory or a distribution center (Geraedts et al., 2012; Hopkinson et al., 2006; Walter et al., 2004).

Moreover, AM will allow companies to produce “low scale parts”—the parts in the company's product portfolio that are manufactured with low volume—without having to invest in expensive tools, such as molds (cf. the long tail). In the particular example of the focal consumer goods manufacturer, mold costs can amount to more than 500,000 Euros, depending on the complexity of the part and the tools. Accordingly, implementing AM can

⁴ On this basis, the focal consumer goods manufacturer has decided to not prefer a particular technology but rather develop on leading technologies (FFF, SLS, and PJM) simultaneously.

reduce the sunk costs and general investments in equipment (Hopkinson et al., 2006). Besides, the reduction and elimination of traditional tooling, such as molds, AM will potentially increase a company's product introduction rate. Since mold and tool development and testing time can be reduced (due to free forming in AM machines), companies will be able to generate more rapid test concepts and release them to the market (cf. Bogers & Horst, 2014; Mortara et al., 2009; Wong & Hernandez, 2012). Furthermore, adjustments to geometries, concepts, new parts for existing products, etc. will be possible after a product has been launched and released to the market. This will enable faster and better reactions to market and trend changes (Hopkinson et al., 2006).

A business model perspective on additive manufacturing: From a manufacturer-centric to a consumer-centric value logic

The above characteristics of AM directly affect how a manufacturer (the focal company in this case) in the consumer goods industry can “do business” by offering value to its customer while also capturing part of that value (Afuah, 2014; Massa & Tucci, 2014; Zott et al., 2011). In this paper, we refer to a business model as a system of interdependent activities within and across the organizational boundaries that enables the organization and its partners to create value and capture part of that value (Zott & Amit, 2010). For example, the fact that free forming and personalization are now possible to a larger extent implies a possible shift of value-adding activities from the manufacturer to the consumer. Besides, advances in Internet capability (the so-called “Web 2.0”) make it even more possible to establish a direct contact between manufacturers and consumers (Wirtz et al., 2010). A major implication of AM technologies is therefore the potential to shift productive activities from the manufacturer to the consumer.

Generally, considering business models for AM is important given that technology itself has no real value to a company if not commercialized in a profitable manner (Chesbrough & Rosenbloom, 2002). While new technologies can sometimes be implemented with existing business models, AM technologies are disruptive to the extent that they may require some reshaping or reinvention of the business model in order to capture its value (Chesbrough, 2010; Johnson et al., 2008). In particular, a major shift involves the transition from a manufacturer-centric to a consumer-centric value logic in the business model, which implies that consumers can be more directly involved in productive and value-adding activities. In the context of consumer goods manufacturing, this has a number of important implications.

Here, we build on Amit and Zott's (2001) framework of efficiency, complementarities, lock-in, and novelty to determine the value creation logic. Table 3 presents a comparison of a traditional manufacturer-centric logic with a new consumer-centric logic within this business model framework. In the table, efficiency refers to cost reductions offered by the manufacturing platform. Ease of accessibility between sellers and buyers, transparency throughout the supply chain, leveraging opportunistic behavior, and accelerating the purchasing process via direct connectivity, all contribute to a potential high efficiency. Moreover, complementarities refer to the ability to offer products and bundles in such a manner that offering them together increases their perceived value for the consumer. This can be achieved by offering after-sale services or complementing products, offline services, offering products that are not directly related to the main product, and products from other providers. Furthermore, lock-in refers to the ability to create loyalty by consumers in order to establish repeating transactions. It aims at rewarding customers for reoccurring purchases, for example through loyalty programs, a strong and favorable design, and customization. Finally, novelty refers to the ability to renew product offerings, which goes

beyond the mere development of products, technologies, production methods, etc. In this case, a first mover strategy can be beneficial as it can contribute furthermore to consumer lock-in.

Insert Table 3 about here

According to the analysis, a central element in customer-centric business models for AM involves a direct co-creation with users, which creates value externally for the consumer. In an extreme case, the creative part can even be done purely by the consumer, or consumers may form strong communities around the design and service based on the AM technology. Lock-in will mainly revolve around the specific experience, which can still only be offered by the manufacturer that owns the platform. Another source of value is the potential differentiation that the manufacturer can offer to create value for the consumer. AM will also enable the production of specialized parts for special edition series and customized products. There is still potential for the manufacturer to offer complementing services, for example by using partnerships with 3D generating software providers, AM platform manufacturers, other accessory providers, or by directly selling services related to the AM process, design rules for the products, material knowledge, etc.

OPERATIONALIZING A CONSUMER-CENTRIC BUSINESS MODEL:

IMPLICATIONS FOR SUPPLY CHAINS

Moving from a manufacturer-centric to a consumer-centric value logic—in the sense that the business model implies more productive and thereby value-adding activities by the consumer—does not only have strategic relevance but it also holds important implications for the operational activities of the manufacturer.

From centralized to decentralized supply chains

The characteristics of a consumer-centric business model based on AM technologies affect the decoupling point between the manufacturer's and the consumer's activities—much in line with Koren's (2010) discussion of the changing role of the customer when moving from mass production to mass customization to personalized production (Figure 1). With respect to the supporting supply chain, this creates the potential and even necessitates a move toward a more decentralized supply chain structure, even though AM could in general be integrated with centralized supply chains as well.

When considering supply chain structures for AM, Walter et al. (2004) describe centralized and decentralized as two possible models. They describe the effect utilizing AM technologies would have on the supply chain, especially considering the long tail in relation to the production of low scale parts (based on Christopher, 1992). Using AM will reduce the inventory levels necessary in distribution centers while keeping a centralized AM production facility. This will allow companies to increase the delayed differentiation and reduce general inventory levels while allowing companies to better fit supply to real demand. Centralized inventory with centralized AM production for low scale parts will decrease inventory while keeping investments low. This means that the company may have the more standardized products on the inventory shelves with high turnover.

Insert Figure 1 about here

This is then supplemented with specialized customer-specific products. In this way, the inventoried components can be produced based on lean principles and kanban signals to replenish the more standardized components and the customized products are manufactured just in time based on the AM technologies. This setup is reducing complexity in the supply

chain (balancing capacity and inventory), decreases the response time, and changes the business model as such, as in line with the mass customization approach (Da Silveira et al., 2001; Pine, 1999; Tseng & Piller, 2003). One of the more interesting debates in recent years concerning supply chain strategy is based on “lean” and “agile” philosophies (cf. Tuck et al., 2007). The focus of lean thinking has been on the reduction or elimination of waste (*muda*). It has been suggested that lean concepts work well where demand is relatively stable and hence predictable and where variety is low (Christopher et al., 2006).

Conversely, in those contexts where demand is volatile and the customer requirement for variety is high, a different approach is called for. This is the concept of “agility”, which is concerned with responsiveness. It is about the ability to match supply and demand in turbulent and unpredictable markets. In essence, it is about being demand-driven rather than forecast-driven, and some of these approaches may fit the AM business model. In some cases, the two ideas of lean and agile can be brought together as a hybrid “leagile” solution (cf. Tuck & Hague, 2006). One such hybrid solution is to utilize lean principles when designing supply chains for predictable standard products and agile principles for unpredictable or “special” products. Or again it may be that total demand for a product can be separated as “base” and “surge” demand. Base demand is more predictable and less risky so that lean principles can be applied, while using agile approaches to cope with surge demand.

At the same time, the free forming nature of AM and the lack of need for tooling enables decentralized production close to the market. Companies can produce decentralized at production facilities close to their customers with a relatively low investment due to the reduction in dedicated tools and the flexibility of AM platforms. This will further reduce inventory and decrease dependency on forecasting. Furthermore, it will decrease lead times in a company’s production while increasing responsiveness for market changes. To exemplify this, Walter et al. (2004) describe a case from the aerospace industry, where

original equipment manufacturers (OEMs) in the industry produce high volume parts in their facilities in a centralized manner—whether using AM or traditional manufacturing methods—while producing low scale parts at decentralized facilities close to their customers. By that, the OEMs were able to reduce inventory costs, increase their responsiveness, lower their investments, and increase their ability to customize products to customers’ needs (Walter et al., 2004).

In the decentralized production system, the business plan will revolve around localization and accessibility. Localization refers to fact that a manufacturer will be able to utilize local brand stores (or other facilities) for the production of low volume parts and by that reduce the inventory needed and its dependency on forecasting. By that, it will be able to increase its responsiveness to market needs and changes. This mainly creates internal value as its benefits are targeted toward its operations. Additionally, localization can also be implemented in a localized product focus, as the manufacturer will be able to tailor products to their markets. Accessibility refers to the manufacturer offering consumers the platforms to print their parts if they do not own one, in addition to offering the knowledge to create a model if they do not possess the knowledge to do so. Using this business model, with a shifting decoupling point that puts more emphasis on the consumer, the manufacturer can create a lock-in as many of its consumers would like to use the service and rely on the manufacturer to do so. Besides internal value, this creates value externally for users and consumers.

Decentralized supply chains for additive manufacturing: A “glocalized” approach

Decentralized supply chains have been introduced and researched as a competitive model since the early 1990s (Hadar & Bilberg, 2012). While decentralized supply chains are in general more flexible and more likely to withstand turbulences, a supply chain model that

presents a further step by stressing the local aspect of supply chains is the “glocalized” approach. This model advocates a local, independent supply chain structure on a global scale, i.e. several locally-minded, self-sufficient supply chains around the globe. The term “glocalization” combines globalization and localization to create a hybrid that will provide the best of both worlds (Robertson, 1994). The glocalization approach emphasizes the coexistence and interpenetration of the global and the local to achieve optimization of companies' business activities (Svensson, 2001).

The local aspect of the glocalized concept calls for a self-sufficient supply chain in such a way that the factory is providing materials, parts, pre-assembled elements, etc. from local suppliers and supply only local customers. The global aspect comes into effect when this structure is implemented in several regions around the globe. Suppliers and partners must also operate on a glocalized structure in order to fully complement it and make the entire supply chain responsive and flexible. Separating the regions of the supply chain and creating alliances with local partners and customers may be part of the new business model. This global production model, with production bases around the world and more diverse supply chains and distribution, is increasingly developed and is becoming particularly relevant for AM business models. Companies need to become more responsive, and reduce transportation and inventory. This creates challenges in transferring tacit knowledge between production sites, securing inventories and quality management, and the growing risk of technology being leaked (Kang, 2010). Accordingly, complex strategic decisions have to be made that integrate various relations of different levels (Jaehne et al., 2009).

Implementing a fully consumer-centric value logic? Toward a personalized model

The characteristics of AM technologies, as presented earlier, give rise to the opportunity to implement a consumer-centric business model through a decentralized supply

chain. While a decentralized production system allows for localization and accessibility of a manufacturer's offer, e.g. through local brand stores, a next step implies an even further movement of the manufacturer-consumer decoupling point, where the consumer takes over productive activities of the manufacturer. The notion of a consumer acting as a producer goes back to at least Toffler's (1980) suggestions that so-called "prosumers" become more important in the face of the digital and information age, the rise of environmentalism, interactive interfaces, etc. Recently, this prosumerism often refers to the use of media, where consumers are also producers of media in which very personalized content replaces the centralized structure—supported by the rise of social media and accessibility of the Internet (Rennie, 2007).

AM technologies have particular potential for customer-centric and personalized production systems as they allow consumer to produce parts, products, and machines, as users of dedicated AM technologies. In such a model, end users of AM can use the technology to produce a variety of parts for themselves and others, which then implies a fundamental change to the global structure of manufacturing, amplifying the change from centralized to decentralized supply chains. The evidence indeed shows an exponential growth in the development of the personal desktop printers between 2007 and 2012 (Wohlers, 2013). Such printers are no longer in the possession of industrial companies and individual innovators but rather infiltrating early adopters as well. Given that the prices of a "personal" 3D printer will continue to drop significantly in the coming years, there is an enormous potential that an increasing amount of consumers will own a personal 3D printer as the technology percolates into the mass market (Wohlers, 2014).

Fully customer-centric production systems emphasize the personalization of manufacturing. Manufacturers can increase the individualization of a specific consumer by offering consumers who own a 3D printer the possibility to print their own parts. An online

platform using a service design could satisfy the supporting business model. While home printing would imply a full implementation of a decoupled supply chain, manufacturers could also provide printing solutions for consumers who create their own designs, which may be shared with others, creating the potential to create a vibrant community (cf. Jeppesen & Frederiksen, 2006; Lakhani & von Hippel, 2003). Payment methods could be charged per print, increasing the profit of a CAD file since it can be used by many users, or as a subscription, which will create a high lock-in. This can also be used to boost manufacturers' current products as designs offered by the manufacturer can be used in the portfolio. In this process, the manufacturer can in principle still keep the original designs (or files) proprietary given it can communicate with the equipment of the consumer who will not need the actual file but rather only the G-Code.

Consolidating the above shows value creation—both externally and internally—for the consumer and for a manufacturer's operations. Internal value creation manifests itself in supply chain and operations as AM provides benefits to solve challenges and create opportunities for mass customization, in particular in consumer-centric models with an emphasis on personalization (Tseng & Piller, 2003). It supports the localized production concept and decentralization of supply chain while still providing value to the manufacturer. External value creation manifests itself in differentiation and personalization for the manufacturer's products and parts. This enables direct manufacturing, taking advantage of the Web 2.0 and online interfaces to enable co-creation with users, which is also an important building block of mass customization and personalization.

CONCLUDING DISCUSSION

This paper presented the state of the art of AM technologies, and it explored how these technologies may influence the viable business models within the consumer goods

manufacturing industry—all with the aim to answer the question how emerging AM technologies impact business model development and operations in consumer goods manufacturing. The empirical base of this research included the general developments in AM technologies, business models, and supply chains, while we also specifically relied on the recent explorations at a leading consumer goods manufacturer within the plastic component industry. In this context, the manufacturer has been particularly interested in the utilization of additive technologies for the production of customer-specific consumer goods on a large scale. This development is fueled by the fact that, in recent years, AM technologies have emerged as a viable manufacturing technology due to significant improvements in part quality, price and manufacturing speed. Below, we will summarize our main findings and further discuss these findings to highlight possible implications and future research directions.

Emerging additive manufacturing technologies and new business models: Toward a consumer-centric value logic

In this paper, we identified six leading AM technologies based on the technologies' capabilities, materials, processes, etc. The six technologies are—FFF, SLS, SLA, DLP, PJM, and Zcorp—were analyzed along a number of relevant parameters to assess their potential (with a focus on the focal manufacturer's requirements and specifications). In our assessment, based on the existing and known technologies for consumer goods, FFF is the leading technology considering its potential as a manufacturing concept—mainly due to the strict nature of the particular industry's chemical standards and the technology's ability to print in color, which is a prerequisite in the consumer goods industry. However, advances in other technologies, for example biocompatible materials in PJM and color technology for SLS, could potentially change this position and make any of them the preferred technology

over time. While this assessment is expected to show the general direction of any assessment in consumer goods manufacturing (where the same characteristics are deemed important), future studies should determine to what extent these findings are generalizable. Practically, this framework could be used as an exercise for manufacturers that are interested in adapting AM as a manufacturing capability, bearing in mind the possible subjectivity of the analyses given the context in which they are analyzed.

These developments in AM technology are expected to change the future consumer goods business models, which describe the logic of how companies can create and capture value from these technologies (Chesbrough & Rosenbloom, 2002; Zott et al., 2011). For incumbents in the industry, adopting AM as a manufacturing concept is particularly challenging given the inherent barriers to business model innovation, such as conflicts with the existing business model and the cognitive frames that prevent managers from understanding these barriers (Chesbrough, 2010). Given that there are different AM technologies available in the market and that traditional manufacturing technologies are still widely used, the case moreover reveals key considerations when exploring or experimenting with new business models (cf. Bogers et al., 2015; Brunswicker et al., 2013; McGrath, 2010).

As a part of the digital revolution, AM presents opportunities for new and innovative business models as well as the utilization of more traditional business models. For example, digital manufacturing enables direct input from consumers and hence enables customization and personalization of products. Advances in Internet capability (Web 2.0) make more direct contact between companies and consumers possible, which in turn will also affect the manufacturer-consumer decoupling point—moving more upstream than in traditional models (cf. Wirtz et al., 2010). Accordingly, there is a shift from manufacturer-centric to consumer-centric business models, which are characterized by a direct co-creation with users (O'Hern & Rindfleisch, 2009; Prahalad & Ramaswamy, 2003; Sawhney et al., 2005). In an extreme

case, the creative part can even be done purely by the consumer, or consumers may form strong communities around the design and service based on the AM technology. Lock-in can be established through the specific experience, which can still only be offered by the manufacturer owning the platform. Another source of value is the potential differentiation and the production of specialized parts for special edition series and customized products.

Designing and implementing old versus new business models: A complementarity perspective

From a product portfolio point of view, the new AM business models will not replace traditional business models, but should be seen as complementary and thus possibly co-existing (Benson-Rea et al., 2013). The mainstream products may still follow the traditional business models, but the personalized consumer-designed products may be on top of that. The new business model may offer a competitive advantage, and it could complement and thereby even augment the value that is captured through the traditional business model. Nevertheless, the potential to disrupt or cannibalize the traditional technologies and business models will also need to be considered (Christensen, 1997; Tushman & Anderson, 1986). This is particularly salient for incumbent manufacturers, given that their capabilities are rendered obsolete in the face of competence-destroying innovations (Tushman & Anderson, 1986; Henderson & Clark, 1990; Hill & Rothaermel, 2003). In fact, the same capabilities that can be critical to a company's old business model may become rigidities that handicap performance in the face of the new business model (Chesbrough, 2010; Leonard-Barton, 1992).

Moreover, AM technologies do not only support a move to a more consumer-centric business model but they can also support the existing business models as they may replace some modules within the entire manufacturing system or architecture. While this modularity

as such can hold important implications for future developments of technologies and business models (cf. Henderson & Clark, 1990; Kodama, 2004), a concrete consideration is how different AM technologies fit together, as more or less connected modules, in the overall strategic framework of the company (cf. Teece, 2010). For example, AM can be used for rapid prototyping and for production or replacement of tools, molds, or other equipment. Figure 2 proposes a possible framework that highlights the possible solutions or shifts within manufacturer-centric and consumer-centric business models as supported by the emerging AM technologies.

Insert Figure 2 about here

How the business models will be implemented, in detail, will have to be further researched. While there are many unknown challenges that will emerge in the future, a particular issue that has not been dealt with so far is the legal liability in the context of increased consumer involvement and responsibility for home manufacturing (cf. Bradshaw et al., 2010). More generally, however, the literature of innovation toolkits has shown a great potential benefit when involving users in such innovation and customization processes (Bogers et al., 2010; Franke & Piller, 2003; von Hippel, 2005), even though the profitability and potential remains to be determined (cf. Piller et al., 2004; Prahalad & Ramaswamy, 2003). Nevertheless, developing the appropriate toolkits and platforms will be required to effectively leverage the latent potential of integrating various stakeholders in the innovation process (Eisenmann et al., 2006; Frankenberger et al., 2013; Gawer & Cusumano, 2014; West & Bogers, 2014).

From manufacturer-centric to consumer-centric business models: Implications for supply chains

Moving toward more consumer-centric business models can be operationalized through a decentralized production system in which the decoupling point within the supply chain is changing due to a larger involvement of the end consumer. Figure 2 includes the supply chain dimension in a proposed framework for AM-based manufacturing solutions. While centralized production refers to printing at the different manufacturer facilities around the globe, a decentralized system breaks this system up into more localized facilities. In a centralized model, the manufacturer can still utilize AM platforms for production of specialized parts for low production series and special editions. It can also increase the freedom of design for designers and enable them to incorporate more unique parts to the products. Moreover, the manufacturer can offer online solutions to enable co-creation with consumers—effectively moving toward a customer-centric model. In this model, the manufacturer can create the platform for users to customize or personalize their own parts and ship them on demand.

This model has the additional benefit that the manufacturer can also use the models created by users as inspiration for novel product designs and as a source of market data gathering. More generally, if the decentralized supply chain connects the manufacturer and consumer through an accessible platform, this direct contact can also be used to collect valuable consumer data—thus linking back to the consumer-centric business model. This could also possibly be used to monitor trends in the industry, ranging from design to purchasing behavior, and it can also be used to generate and establish a co-creation platform (Sawhney et al., 2005; von Hippel, 2005).

From a supply chain point of view, decentralized production can manifest itself as manufacturing with AM technologies in several brand stores around the world. In this

structure, production of low scale parts can take place close to the consumers to enable production to real demand. In doing so, the manufacturer will be able to reduce its inventory levels in the distribution centers close to the markets and increase its responsiveness simultaneously. Furthermore, the manufacturer can offer a user experience around AM for its consumers, especially for the ones who are uneducated in 3D modeling and printing. This would also enable a “globalized” supply chain in which a company localizes its global production system, effectively separating global supply chain modules into disconnected parts, which each rely on local input and output. The AM technology in combination with scarcity of resources and volatility in commodities and raw materials are some of the reasons for consumer good manufacturers to re-examine their business models and global footprints (Hadar & Bilberg, 2012). Further research is needed to better understand and respond to the challenges of globalization locally (Hesse & Rodrigue, 2006), and especially in direct relation to the supply chain and production—the old norms of “local for local” manufacturing in favor for the new “global village” (Christopher et al., 2006).

Taking a further step in the decentralized consumer-centric production system, the manufacturer can provide a platform for home printing (sometimes referred to as the “prosumer” approach). In this case, the manufacturer can offer truly personalized parts for home printing, in addition to low volume parts, which will not be financially justified with traditional production methods. The manufacturer will have to create an online platform for users to create, share, or download geometrical models and files for printing. This will naturally open new possibilities for the manufacturer to create interactive platforms in addition to “outsourcing” the production of specialized parts to the consumers.

Business model and supply chain challenges of additive manufacturing

While one of the advantages of AM is the ability to co-create with consumers in order to increase the customization of unique parts, the question here is how the manufacturer can manage and control that process. Giving consumers the ability to contribute to the design will increase individualization but at the same time demand the company to approve every unique design for safety, mechanical behavior, etc. Additionally, if the company would like to keep control of the designs that the consumers contributed to, it will tremendously increase the number of parts and thereby the supply chain complexity. In a purely decentralized setting, it is virtually impossible to handle such large variance. Moreover, if consumers print at their own home—based on the many platforms for 3D printing that are or will be available—how will companies make sure the printing parameters fit the design specifications? Consumers will be able to print with many materials and with platforms that have different specifications. That would mean that the final product will be different depending on the platform, which will make it very hard to guarantee a part behavior or properties. A question of legal liability thus also arises when parts are not being centrally produced and approved in the official manufacturer's processes.

The changes in the production decoupling point between the manufacturer and the consumer moreover have legal implications depending on whether or not the manufacturer keeps control of the original designs (or files) or the underlying source code. At the same time, a possible consideration is the parallel industry development in 3D scanning, which refers to the ability to transform physical objects to digital files. This could further enable copying and sharing of digital designs and files over the Internet. Drawing a parallel to the music and movie industries, the digitization of music and movie files by consumers involved copying and (freely) sharing these files, while it took the industry a long time to develop viable business models in this domain (e.g. Spotify and Netflix). All-in-all, future

developments within a decentralized supply chain that supports AM-based business models will need to consider the intellectual property (IP) implications (cf. Bradshaw et al., 2010). Possible implications are a change in IP and licensing strategies (Bogers et al., 2012) or in IP sharing norms more generally (Fauchart & von Hippel, 2008; von Hippel & von Krogh, 2006).

Yet another parallel process that may challenge the opportunities that a manufacturer has is the design and production of 3D printers. This development will affect the AM-based business models and supply chains given that the availability and offering of 3D printers will become part of the value creation process and related cost structures within a consumer-centric value logic. Besides the actual functionality and delivery, this for example refers to the design of 3D printers, which is currently still inspired by their rapid prototyping functionality (and look). Machines are generally built for a lot of manual handling and are not optimized for a production layout. The printing process relies on many post-processes, which adds complexity to the supply chain and inaccuracy to the process.

Complementarities between technology, business models and organization

Our investigation of the implication of AM technologies on business models and supply chains in the consumer goods industry has provided the state of the art of available technologies in this particular domain. This study showed how such a technology concept is fundamentally intertwined with the business model concept. As in line with Baden-Fuller and Haefliger (2013), this co-evolution implies that the technological developments directly relate to certain business model decisions. As they also highlight, these decisions involve openness and user engagement, which in this case implies a consideration of how the business model needs to align with the relevant knowledge sources within or outside the organization to create and capture the most possible value (cf. Chesbrough, 2003; Chesbrough &

Rosenbloom, 2002). This directly contributes to our understanding of open innovation, which is a distributed innovation process based on purposefully managed knowledge flows across organizational boundaries in line with the organization's business model (Chesbrough, 2006; Chesbrough & Bogers, 2014; Vanhaverbeke & Chesbrough, 2014). Specifically, we provide a framework for understanding how the co-evolution of technology and business models links to the organization of productive activities, thus directly extending this general understanding to the context of (innovative) supply chains. What become clear in this context is that there are strong complementarities in this innovation process, not only across these concepts but also within, such as the interdependence between product and process development (cf. Kraft, 1990; Reichstein et al., 2008).

This interdependent development of technology and business models further highlights the role of supply chain structures to create and capture value. More generally, the case reveals that, whichever combination of AM technology and business model emerges, there are important implications for how the company organizes its activities. The choice between a manufacturer-centric and consumer-centric business model has a significant impact on the organizational structures and capabilities that would support the operationalization of the (new) business models. Therefore, considering a business model as a system of interdependent activities (Zott & Amit, 2010), there is an important connotation to finding new ways to “organize” these activities (Casadesus-Masanell & Zhu, 2013; Foss & Saebi, 2014). It is therefore important to consider the co-evolution of technology and business models in relation to the organizational structures that enable the organization to enact the commercial opportunity they identify (George & Bock, 2011).

This co-evolution between technology, business model and supply chains (or organization more generally) is an important avenue for future research, while it also holds important implications for practice. On the one hand, it needs to be better understood how the

general developments in technology affect existing and future business models, and vice versa, while we identify the specific role of the supply chain and organization in general (e.g. structure and capabilities) as being a particularly important factors in this process. Besides, the specific developments in the consumer goods industry will need to be further scrutinized in order to better understand the particular contingencies in this industry. Particular attention will need to be paid to the implementation of new technologies, business models and organizations, given that this will provide a specific set of challenges that go beyond the development phase as considered in this paper.

On the other hand, this paper gives some insights into the state of the art of the developments within AM technologies and promising business models with supporting supply chain, which may be of relevance to other practitioners within consumer goods and beyond. As such, the paper implies certain attention points for managers who need to deal with new developments in technologies, business models and supply chains—within AM and beyond—such as a set of key evaluation criteria, key considerations for business model and related supply chain development based on new technologies, and the importance of considering operational and organizational issues in the face of technological and business model development.

Finally, some key practical takeaways include the presentation and benchmarking of the leading AM technologies (Tables 1 and 2), which give a concise overview of the state of the art in terms of production technologies for the consumer goods industry. Managers could use these insights as reference points for their own explorations within AM, while also offering the basis for considering more consumer-centric business models in which they will need to manage the changing decoupling point in the consumer goods' manufacturing supply chain. Accordingly, business model development in the face of emerging AM technologies implies managing organization change and more openness toward external sources. A

balanced view will be needed though as an increasing consumer role can have major implications for technologies, business models, supply chains, intellectual property, and so on, while also the threats, costs and downsides will need to be managed. Moreover, given that the uncertainties surrounding AM technologies and business models, companies will need to explore or experiment with new developments, including organizations and supply chains (Baden-Fuller & Haefliger, 2013; Bogers et al., 2015; Brunswicker et al., 2013; Koren, 2010; McGrath, 2010). Managing all these processes in parallel could create certain paradoxes, which will need to be balanced with the right leadership and strategies (Benson-Rea et al., 2013; Bouncken et al., 2015; Chesbrough, 2010; Laursen & Salter, 2014; Smith et al., 2010). And given the holistic nature of the framework and solutions that can or may be derived from AM technologies and business models, it will advantageous to consider the possible benefits for or effects on other domains and functional areas, beyond R&D and manufacturing, such as marketing or entrepreneurship (Chesbrough & Bogers, 2014; Coombes & Nicholson, 2013; Ehret et al., 2013; George & Bock, 2011).

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TABLE 1**Leading additive manufacturing technologies for consumer goods manufacturing**

AM technology	Description
Fused Filament Fabrication (FFF)	A process in which a filament (a string of plastic) is fed to a heating element (the nozzle) and is then semi-molten in order to be able to dispense the plastic as desired.
Selective Laser Sintering (SLS)	A process during which thin layers of polymer are being distributed in the building chamber and are bound with the use of a laser deflection system (mirrors deflect the laser beam to a desired location).
Stereolithography Apparatus (SLA)	A process of solidifying liquid resin (usually either acrylic or epoxy) by photo-polymerization using a controlled laser beam.
<i>(also: SL)</i>	
Direct Light Processing (DLP)	A process, very similar to SLA, that is also based on a photo-polymerization process; however instead of using a laser beam, a light projector is projecting images onto the polymer surface.
Polyjet Matrix (PJM)	A process that uses the familiar concept of inkjet printing, as used by 2D printing companies worldwide. Instead of using ink, the print head ejects a photo-polymer material that is then hardened by a UV light that is connected to the print head on both its sides.
<i>(also: Inkjet 3D printing)</i>	
Inkjet ZCorporation technology (Zcorp)	A powder-binding process based on a liquid binder (often colored) that is dispensed on to a bed of plaster powder, layer by layer, using an inkjet multi-nozzle printing mechanism.

Note: Assessment based on focal manufacturer, active in the plastic component industry

TABLE 2

Benchmarking additive manufacturing technologies for consumer good manufacturer

		FFF	SLS	SLA	DLP	PJM	Zcorp
Mechanical properties	The strength, dimensional accuracy, elongation, fatigue, etc. of the printed part	3	3	2	2	3	1
Chemical properties	Toxicity, viscosity, etc., of the printed part	5	5	1	1	2	1
Visual finish	The surface quality of the printed part	2	3	5	5	4	2
Cost	The manufacturing cost of the part, including material, production, post-processes, manual processes	5	2	1	1	1	1
Time	The time it takes to manufacture a part, including preparation, production, post-processes	1	1	1	1	1	1
Volume	The possible volume a machine can output per printing job considering build speed, chamber size, etc.	2	2	2	2	2	2
Multicolor	The ability of the platform to manufacture a part in a single color without post-processing	4	2	1	1	4	4
Decoration	The ability of the platform to create color patterns on the part while manufacturing	1	1	1	1	4	4
Sum of scores		23	19	14	14	21	16

Note: 5 represents high (optimal) results, 1 represents low (critical) results.

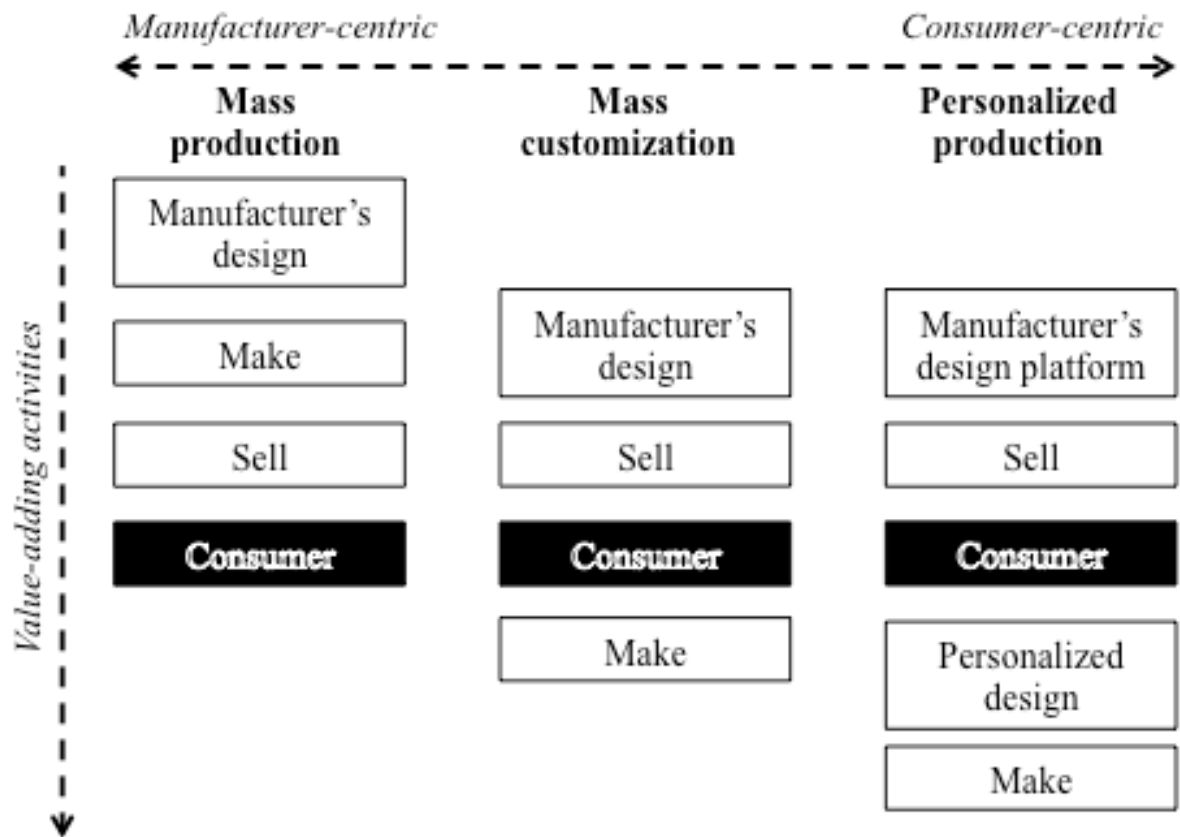
TABLE 3**Comparison of manufacturer-centric and consumer-centric business models**

	Manufacturer-centric	Consumer-centric
Efficiency	<ul style="list-style-type: none"> • Process transparency • Economies of scale • Quality monitoring 	<ul style="list-style-type: none"> • Low inventory cost • Print on demand • Low operating cost • Model reuse
Complementarities	<ul style="list-style-type: none"> • Portfolio-centric product development • Designer creativity 	<ul style="list-style-type: none"> • Indirect linkage to portfolio and product designers • Multi-partner platforms
Lock-in	<ul style="list-style-type: none"> • Direct relation to product portfolio • Company-centric community and sharing 	<ul style="list-style-type: none"> • Support in creation and printing • Availability of platforms • Community-driven sharing
Novelty	<ul style="list-style-type: none"> • Freedom for designers • Unique design for special editions • Co-creation optional 	<ul style="list-style-type: none"> • Co-creation central to design • Personalized designs • Localized markets • Optional subscription

Note: Analysis primarily based on assessment at focal consumer goods manufacturer

FIGURE 1

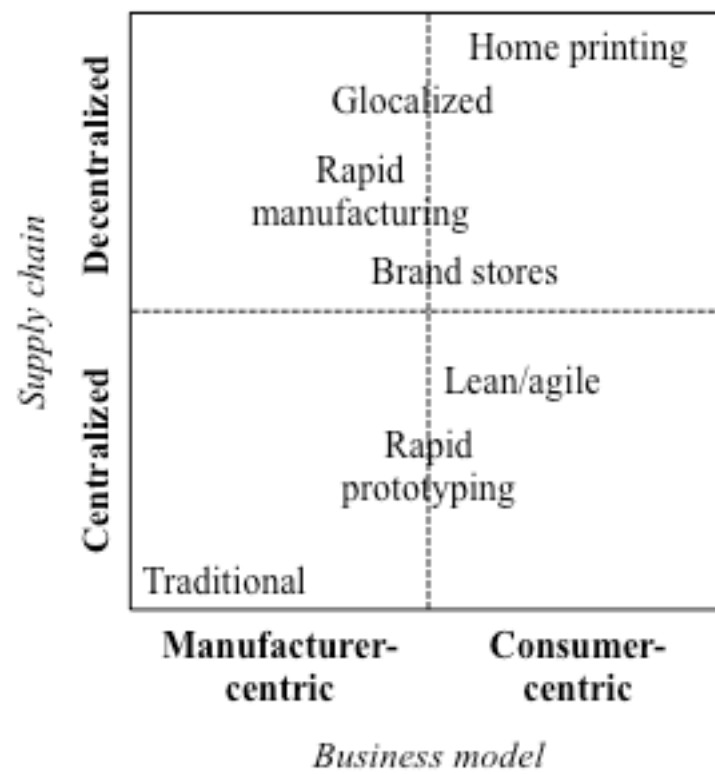
From a manufacturer-centric to a consumer-centric value logic



Note: Adapted and adjusted from Koren (2010)

FIGURE 2

A framework for AM-based solutions in business models and supply chains



APPENDIX A

State of the art of additive manufacturing technologies

In order to understand the different additive manufacturing (AM) platforms and technologies, we present a detailed state of the art analysis of AM technologies. The analysis explores the different AM technologies' advantages and disadvantages, and their feasibility for consumer goods production with a particular focus on the focal manufacturer that serves as an example for the more general developments within the consumer goods industry.

Exploring additive manufacturing technologies

Before presenting an overview of the state of the art, we note that the technologies explored in this paper are polymer AM production technologies alone. Several technologies use metal as well for rapid tool manufacturing and general metal production, such as Selective Laser Melting (SLM) or Metal Selective Laser Sintering (MSLS). Other technologies use wax and ceramics as base materials. These technologies will not be explored in this paper as the focus (in the consumer goods manufacturer that serves as the empirical base) is plastic parts production for consumer goods.

In cooperation with the focal manufacturer, leading technologies have been identified considering the technologies' capabilities, materials, processes, etc. and in light of the manufacturer's requirements and specifications. Six leading potential technologies used for rapid prototyping and AM have been identified, namely: Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Stereolithography Apparatus (SLA), Direct Light Processing (DLP), Polyjet Matrix (PJM), and Inkjet ZCorporation technology (Zcorp). The following section will give a brief overview of each technology, its method of operation, and its main use today.

Fused Filament Fabrication (FFF)⁵

FFF is a process in which a filament (a string of plastic) is fed to a heating element (the nozzle) and is then semi-molten in order to be able to dispense the plastic as desired. Since the material dispensed from the nozzle is in a semi-molten state, it binds with the layer beneath it to create a solid object (Figure A.1). The printing head often moves in the x and y directions while the platform itself moves in the z, although in some machines the print head is capable of moving in all 3 directions (Ahn et al., 2002, Gibson et al., 2010).

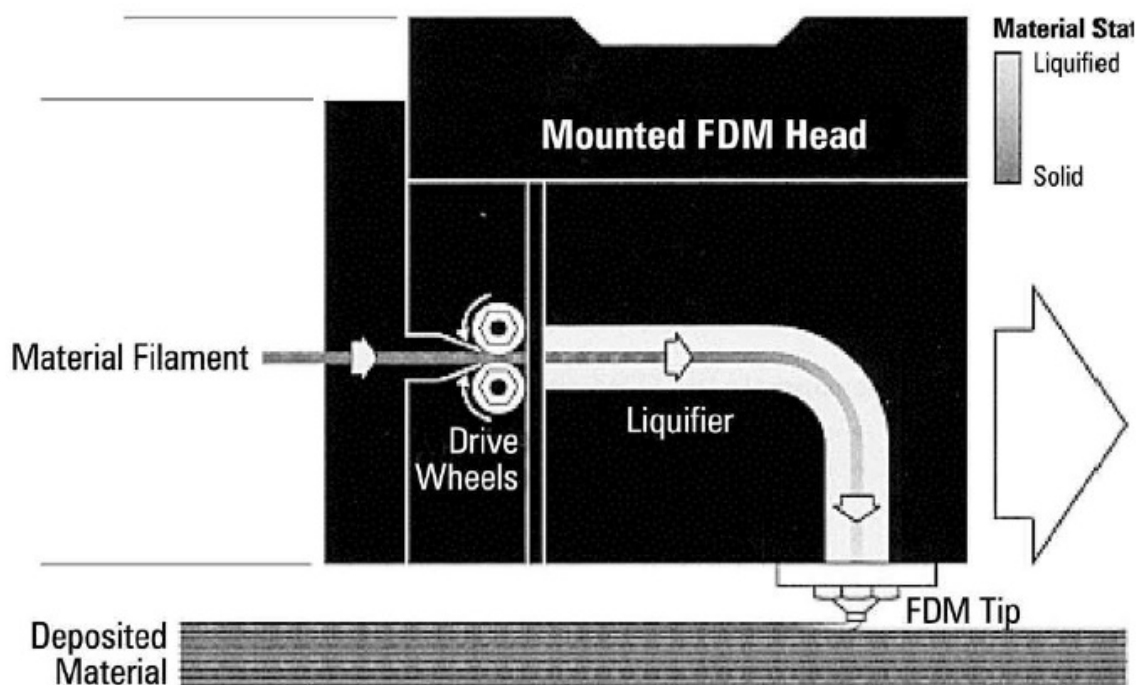


Figure A.1: The FFF (FDM) process (Ahn et al., 2002)

In addition to the building material, high-end platforms use a support material disposal system as well. This support material is used to create geometries that would otherwise collapse in the process of building. The support material is then extracted (usually dissolved), leaving only the building material behind. Common materials used in FFF are

⁵ Fused Filament Fabrication (FFF) is also referred to as Fused Filament Fabrication (FDM), which is a trademark of Stratasys.

mostly ABS and PLA, though some applications require specific materials to be developed.

An example for that is the Ultem 9085 material, which is used mainly for the aerospace industry (Stratasys, 2013a).

The main supplier of industrial FFF machines is Stratasys LTD. which is based in Rehovot, Israel and Eden Prairie, Minnesota, USA. The industrial machine series is referred to as the Fortus series and consists of 4 machines: the Fortus 250mc, 360mc, 400mc, and 900mc, and they differ by the size of the chamber, tip sizes for production, production speed, and other variants. The smallest layer thickness available in FFF is 0.127 mm (0.005 in.) and is available in the Fortus 250mc, and 360mc. The tip size chosen also has a great influence on the accuracy of the part. There are several tip sizes available, such as T16 (0.016 in. in diameter), T12 and T10, correspondingly. Though a smaller tip size and layer thickness will yield in higher accuracy and better surface finish, it will also compromise the mechanical property of the part as less material applied will translate to less binding surface and consequently worse mechanical integrity. Changes in tolerances will of course influence the dimensional accuracy of the part. Different systems have different dimensional accuracies, depending on their mechanics and input parameters (Wholers, 2013, Ahn et al., 2002, Gibson et al., 2010, Stratasys, 2013b).

Selective Laser Sintering (SLS)

SLS is a process during which thin layers of polymer are being distributed in the building chamber and are bound with the use of a laser deflection system (mirrors deflect the laser beam to a desired location). The laser will create a path in the polymer's layer that will consolidate the layers. After the binding of a layer takes place, a new layer will be dispensed and the process will repeat itself until a shape is created (Kruth et al., 2003; Kruth et al., 2005).

SLS machines use different variance of technologies and methods for the process. Different platforms use, for example, different power dispensing mechanisms (arcing vs. linear), different atmospheres (different gases used in the chamber while producing have different affects of the processes), and different laser techniques (different mirrors, different sizes, intensity, etc.). Figure A.2 shows a visual representation of the principal concept (Kruth et al., 2005). SLS machines do not use support materials as the un-bound powder left in the chamber is used as a support structure for the coming layers. This restricts to a certain degree the dimensions and geometries possible with SLS technology (Gibson et al., 2010).

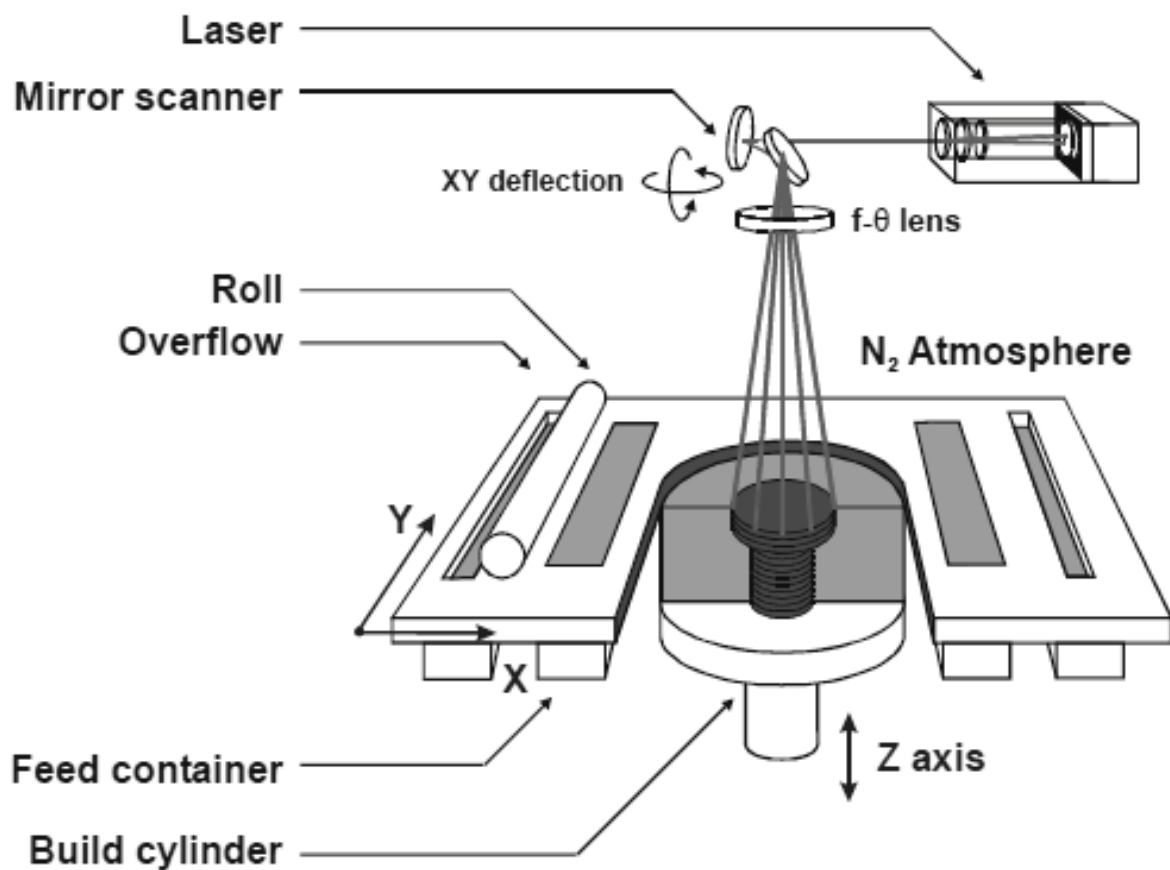


Figure A.2: The SLS process (Deckers et al., 2002)

One of the main suppliers of SLS machines is EOS GmbH with its headquarters in Munich, Germany. EOS's industrial AM machines are mainly of the EOSINT series, which,

in relation to production, comprise of the P395, P760, and the P800. Other machines from EOS include the Formiga series, which is designed for rapid prototyping more than for production. Most SLS machines use different PA powders, though some applications required reinforcing additives, such as glass, aluminum, and carbon fibers (EOS, 2013). The majority of materials used in SLS are white although some materials are offered in black as well. Coloring is only possible with the use of post-processes.

The main difference between the different platforms is the building chamber's size. Layer thickness in the machines can reach down to between 0.06 and 0.18mm, depending on the size of the laser and production parameters, and the building speed can be as fast as 30 mm/h. Going down in layer and beam size will increase the details and the accuracy of the part but will reduce the speed of the process. The higher models (P760 and P800) use a twin laser system in order to increase the building speed (EOS, 2013)

Other than by EOS, the SLS systems is offered by 3D Systems Inc. with its headquarters in Rock Hill, SC, USA. 3D Systems' SLS AM series is the sPro series with a variety of machines from the sPro 60 SD to the sPro 230 HS, which differ mostly by their chamber size. The platform can reach a layer thickness between 0.08 to 0.15 mm and a building speed between 1 and 5 L/h (3D Systems, 2013a).

Stereolithography Apparatus (SLA)

SLA (occasionally referred to as SL) is the process of solidifying liquid resin (usually either acrylic or epoxy) by photo-polymerization using a controlled laser beam. The laser creates patterns on the surface of the resin, and to a degree of depth inside the resin, forcing it to solidify when exposed to the UV light. The building platform is then pulled down, the part is covered with a new layer of liquid resin, and the process repeats for the full formation of the part. Post processing in UV curing oven is necessary after the part is removed from the

machine due to the high viscosity of the resin in order to ensure that no liquid or partly liquefied resin remain on the part. Figure A.3 shows a representation of the process (Gibson et al., 2010; Melchels et al., 2010). Materials used in SLA are either transparent or white and cannot be colored during the process but with use of a post-process (grey colors are possible on some platforms).

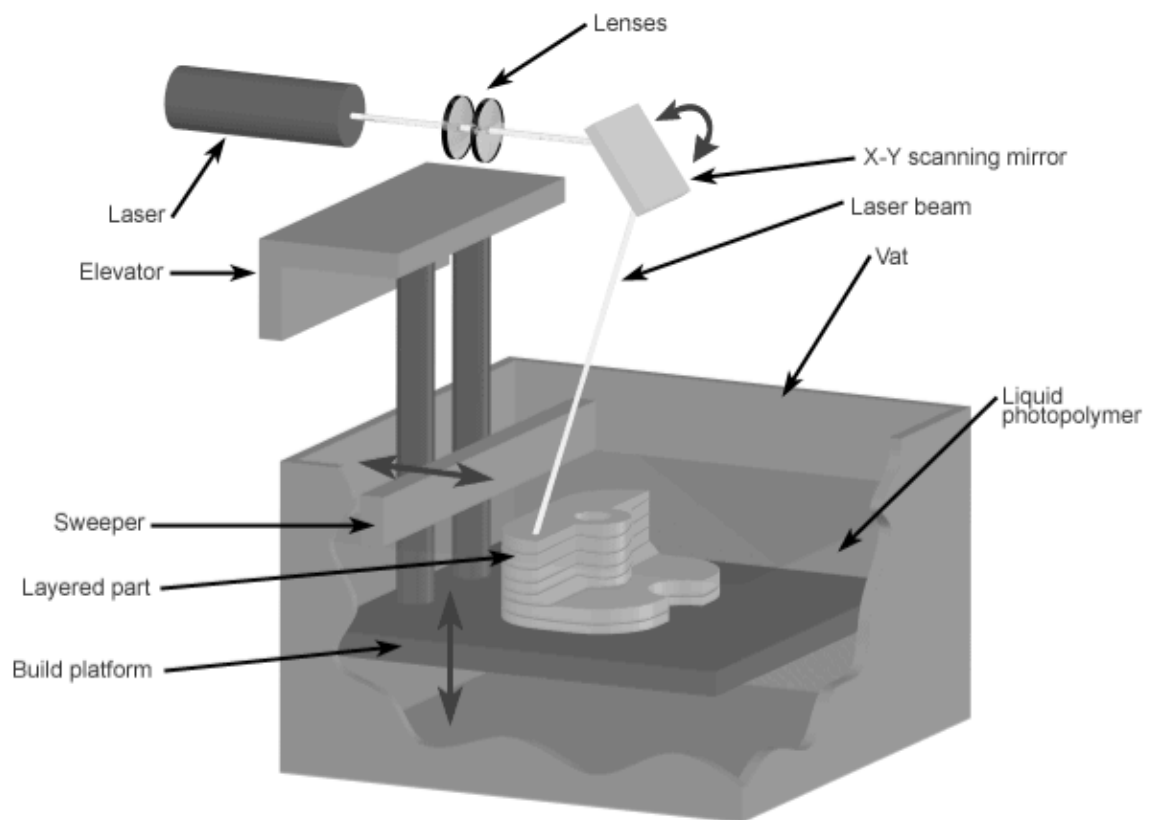


Figure A.3: The SLA process (<http://www.custompartnet.com/wu/stereolithography>)

One of the main suppliers of SLA machines is 3D Systems. 3D Systems has a wide range of SLA machines used for production from the iPro series, namely: 8000, 8000MP, 9000, 9000XL, which differ mostly on print size capabilities. 3D Systems machines can achieve a layer thickness of between 0.05 – 0.15 mm and due to the liquid characteristic of its resin, can achieve down to a micron level accuracy. The iPro machines operate with a dual laser spot size capability for faster building rate, with a beam size of 0.13 mm in diameter for

borders and 0.76 mm for filling (Melchels et al., 2010; 3D Systems, 2013b; Pham & Gault, 1998).

Direct Light Processing (DLP)

DLP is a very similar process to SLA. DLP is also based on a photo-polymerization process; however instead of using a laser beam, a light projector is projecting images onto the polymer surface. Contrary to SLA, in which the platforms moved downwards as patterns are projected on it, DLP's light projector is located under the platform and patterns are projected onto a clear tray that contains the resin, curing the resin from beneath. The platform holding the part will then move up and a new layer of resin will be applied on the tray, as can be seen in Figure A.4. Due to its light projecting technology that project a 2D image and not a single point laser, building time can be significantly reduced and numerous parts can be built simultaneously (Melchels et al., 2010; Gibson et al., 2010).

One of the main suppliers of DLP technologies is EnvisionTEC with its headquarters in Marl, Germany. With its Perfactory series, EnvisionTEC has introduced a wide range of printers used for both rapid prototyping and AM. Interesting platforms for manufacturing are the Perfactory Standard and Xtreme product ranges. Print resolution in these machines can go down to 0.05 mm with a 25 mm/h building rate. Layer thickness can vary between 0.025 to 0.15 mm depending on the material and the platform used. Materials used in the DLP technology are essentially the same as are used in SLA – epoxy based photopolymers. The materials are mostly transparent or have a yellow/red color to them (EnvisionTEC, 2013). Color printing is not possible without the use of post-processing.

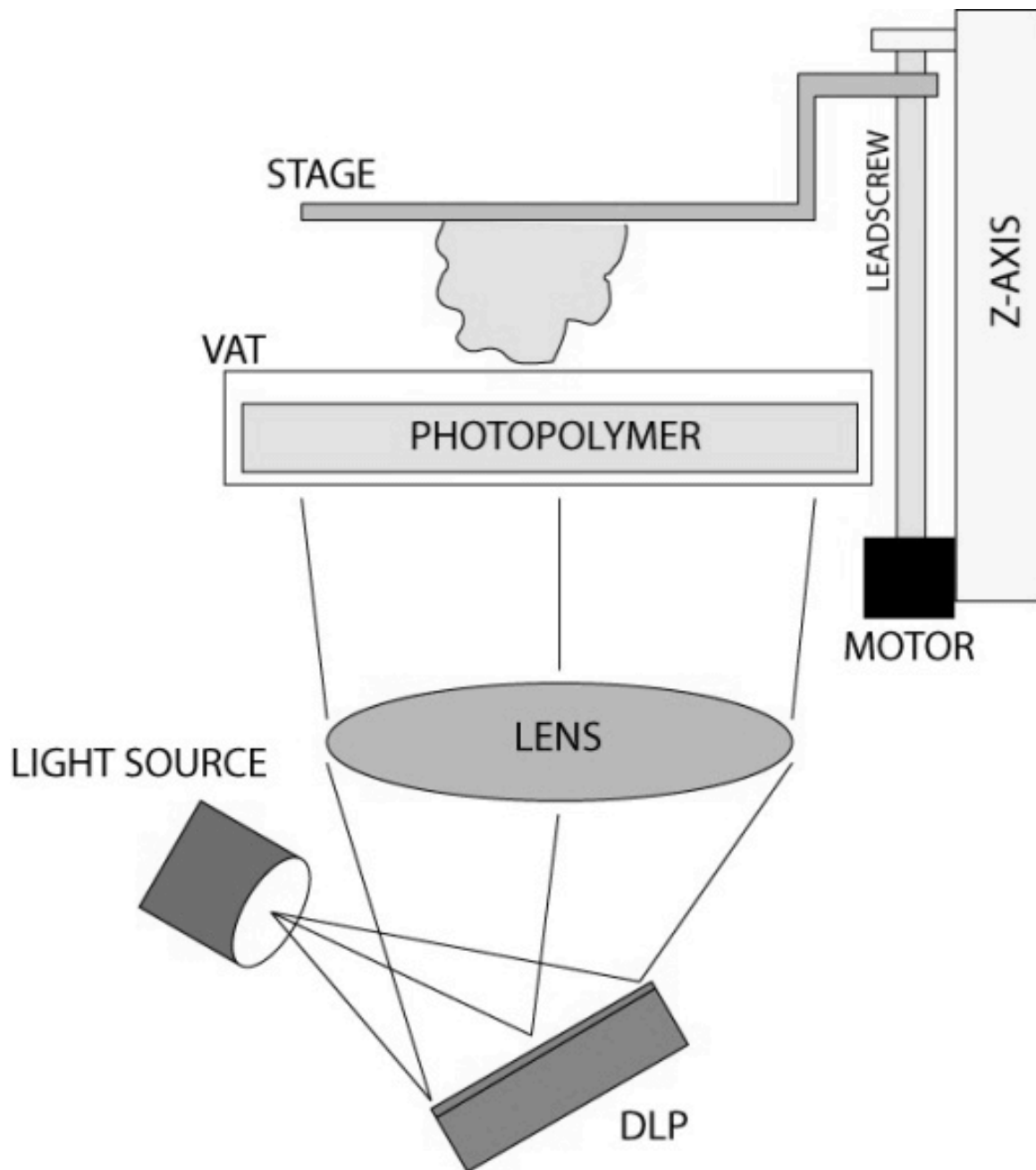


Figure A.4: The DLP process (<http://3dprinterdlp.com/definition-and-technology/>)

Polyjet Matrix (PJM)

PJM (often referred to as Inkjet 3D printing) is one of the youngest AM technologies currently available on the market. It was commercialized by the former Israeli company Objet, which merged with Stratasys in 2013, and is now offered by Stratasys (Stratasys,

2013c). The technology uses a familiar concept of inkjet printing, as used by 2D printing companies worldwide. Instead of using ink, the print head ejects a photo-polymer material which is then hardened by a UV light which is connected to the print head on both its sides, as can be seen in Figure A.5. In addition to the building material applied by the print head, a wax based support material is applied in order to expand the range of geometries achievable by the machine. The support material can be removed using pressurized water (Vaupotič et al., 2006; Brajliah et al., 2006).

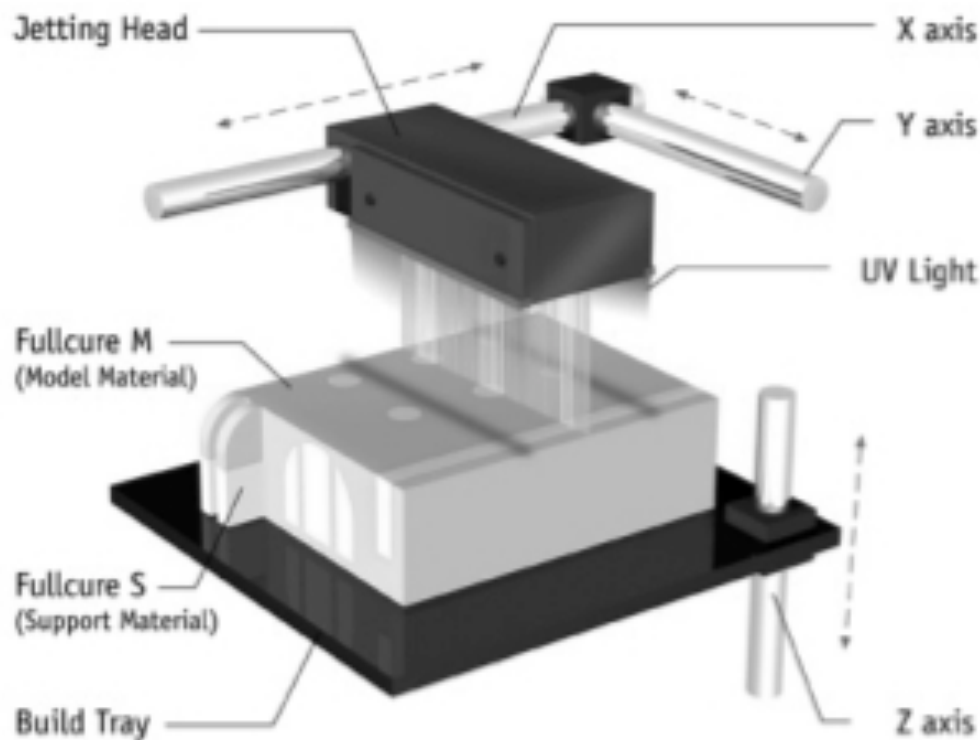


Figure A.5: The PJM process (Vaupotič et al., 2006)

Although the technology is advertised as specialized for rapid prototyping and not for AM, it is one of the fastest and more accurate free forming 3D printing technologies in the market. The speed of the process is attributed to two characteristics of the technology. The first is the multiple ejection of material from the print head and the second is the dual UV

light system in both sides of the print head. Both attributes enable the production of multiple parts simultaneously and a faster curing process (Melchels et al., 2010).

Stratasys has several product ranges it is commercializing: the Eden and the Connex. Suitable printers for AM are potentially the Objet Eden 350V and 500V, and the Objet350 and Objet500 Connex. Layer thickness is specified as 0.016 mm with accuracy of about 0.085 mm, depending on geometries and materials (Stratasys, 2013c). Materials vary from ABS and PP like materials to rubber materials. Several platforms are able to combine soft and hard materials and create different hardness to the finished products. Other platforms can print with the full CMYK color range to a high resolution (Stratasys, 2013d).

In recent years, a growing interest in the biomedical and dental industry gave rise to interesting developments in materials in SLA, DLP, and PJM technologies. Biocompatible materials targeting these applications have been developed in the dental, hearing aid, prosthetics, etc. industries. These epoxy or acrylic based materials were developed to withstand harsh health regulations in these industries (Stratasys, 2013d; 3D Systems, 2013c).

Inkjet ZCorporation technology (Zcorp)

The last technology that has been one of the main ones as explored by the focal manufacturer is the Zcorp powder-binding technology made commercial by Z Corporation, which was bought by 3D Systems in 2012. The powder-binding 3D printing technology (hereafter: Zcorp) was initially developed at Massachusetts Institute of Technology (Sachs et al., 1993) and was licensed to Z Corporation. The Zcorp technology is based on a liquid binder (often colored) that is dispensed on to a bed of plaster powder, layer by layer, using an inkjet multi-nozzle printing mechanism. The drops applied by the mechanism are colored as they are applied (by combining basic colors, similar to a regular printer) hence the printer is capable of printing the entire CMYK color range. Zcorp does not use support materials as it

is built very similarly to SLS while unbound material is used for support, as can be seen in Figure A.6. The remaining unbound powder is removed manually using a vacuum system and is mostly reused again (Gibson et al., 2010; 3D Systems, 2013d).

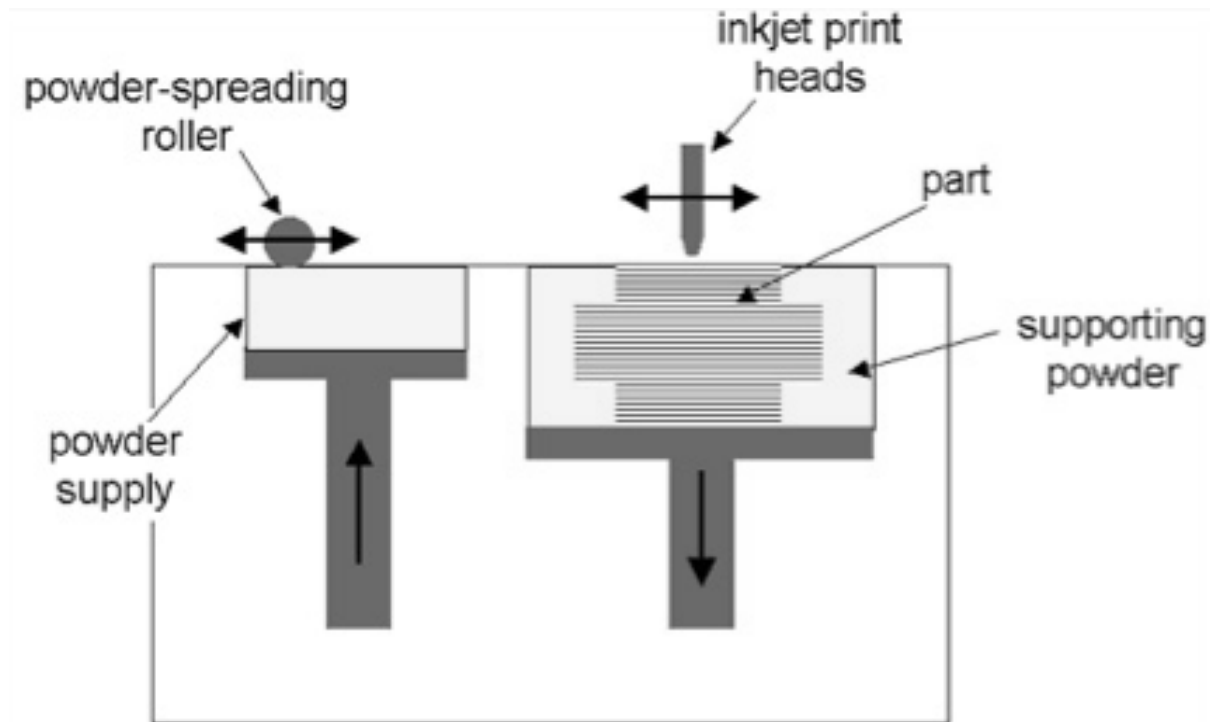


Figure A.6 – The Zcorp process (Sachs et al., 1993)

Some of the larger machines used for higher volume production are the ZPrinter 450, 650, and 850. Layer thickness varies between 0.09 – 0.2 mm. Materials used in the technology are mostly ceramic composite powders and elastomers, although other materials, such as sandstone can be used as well (Gibson et al., 2010; 3D Systems, 2013d; Walters et al., 2009). Though it is clear that Zcorp machines are not meant for production, they nonetheless have some interesting characteristics for the development of AM.

Other manufacturers

Although the companies mentioned above are clearly the market leaders (Wohlers, 2013; Gibson et al., 2010), there are several other companies with manufacturing platforms that hold some potential. For example, the Germany-based Voxeljet has developed a technique that is similar to the Zcorp technology. In this process PMMA plastic is bound with a layer thickness of 0.08 – 0.2 mm and dimensional accuracy of 0.55 mm. The innovative concept is that the system prints in a 45 degree angle and an input and output on the sides of the machine, which enables a potential infinite part construction (Voxeljet, 2013).

Another potential technology that is still in its infancy is called Selective Heat Sintering, which is commercialized by Denmark-based Blueprinter. The technology is very similar to SLS and uses the same materials. The main difference is the use of a heating element instead of a laser to bind layer of the powdered material. The achievable layer thickness is currently 0.1 mm with a building speed of 2-3 mm/h (Blueprinter, 2013). The technology is still under development but could be interesting in the near future.

Yet another interesting development in the AM industry is when injection molding giant Arburg revealed its Freeformer 3D printer. The printer utilizes the newly developed technology Arburg Plastic Freeforming (AKF, after the German abbreviation). The novelty of the technology is the use of the exact same screwing mechanism used in injection molding, which melts granulate to its moldable state. The melted granulate is then applied drop by drop onto a moving platform. This development is groundbreaking because it enables manufacturers to use the same materials they have been using to date in injection molding. This is not only beneficial for material and mechanical properties of parts but also for the reduction of part cost as normal granulate is much cheaper than currently offered AM materials. Moreover, Arburg combined a 5-axis robot to its moving platform that enables construction on the part from its side (Arburg, 2013).

APPENDIX B:

Assessment of additive manufacturing technologies in consumer goods production systems

Mechanical properties

Table B.1 shows part of the mechanical testing conducted in order to assess the mechanical properties of the different technologies and benchmark those to current traditional injection molding. Tests conducted during these experiments are tensile tests and modulus, impact tests, fall, and break tests. FFF parts were tested from two manufacturers: Stratasys as a high-end industrial printing manufacturer, and Makerbot as a low cost desktop printer manufacturer. The purpose was to compare high-end parts with low-cost parts. Additionally, two PJM materials were tested to examine the difference of their mechanical properties, and SLS and SLA parts as well. All these results were compared to injection molded parts, also represented in the table.

The best results were obtained by FFF parts printed on an industrial machine and SLS parts. A surprising factor was the mechanical tests obtained from PJM parts that presented impressive mechanical properties. Two noticeable differences are between FFF parts manufactured in high-end machine and the direction of their production. As can be seen by the tensile modulus, FFF parts manufactured on the Fortus platform presented high results which are comparable to molded parts while the low cost printer yielded poor results. Also, parts manufactured on the Y direction (on their side) present significantly better results than those manufactured on the Z direction (up right), as can be seen in Figure B.1.

Table B.1: Mechanical testing for AM and molded parts

Material	Tech	Layer Thickness (mm)	Color	Type/Variant	Fall Test (cm)	Impact Test w. notch (KJ/m ²)	Impact Test w.o. notch (KJ/m ²)	Tensile Modulus (N/mm ²)	Tensile Test/UTS (N/mm ²)	Break (N/mm ²)	Direction
2C Epoxy	PJM	0,016	VeroGray FullCure850	Objet	9	2,22	28,32	2007,69	63,42	46,27	Y
2C Epoxy	PJM	0,016	VeroClear FullCure810	Objet	12	1,48	23,7	2712,79	58,38	50,81	Y
ABS	FFF	0,3	Green	MakerBot	11	11,78	11,67	1764,75	26,23	25,66	Y
ABS	FFF	0,127	Nature	Stratasys	14	%	22,52	2401,2	36,02	57,4	Y
ABS	FFF	0,127	Nature	Stratasys	14	3,01	3,3	1424,7	8,22	8,22	Z
2C Epoxy	SLA	0,05	Accura Xtreme Grey	3DS	16	1,93	18,74	1687,3	45,34	41,45	Y
PA2200	SLS	0.06	White	EOS	25	13,98	35,8	1665,67	48,34	42,57	Y
ABS	Molding						24,2	2301,32	49,3	32,31	-

Chemical properties

FFF and SLS both scored high in the chemical properties evaluation. The first reason is that they are both familiar materials to the focal manufacturer and are in fact used in the injection molding process. That means that the general material properties and behavior are familiar to the manufacturer and are approved for use in consumer goods. The second reason is that these thermoplastic (ABS and PA) have both already withstood the harsh requirement for chemical approval specified by the manufacturer. That will ease the integration and acceptance of the materials in the organization.

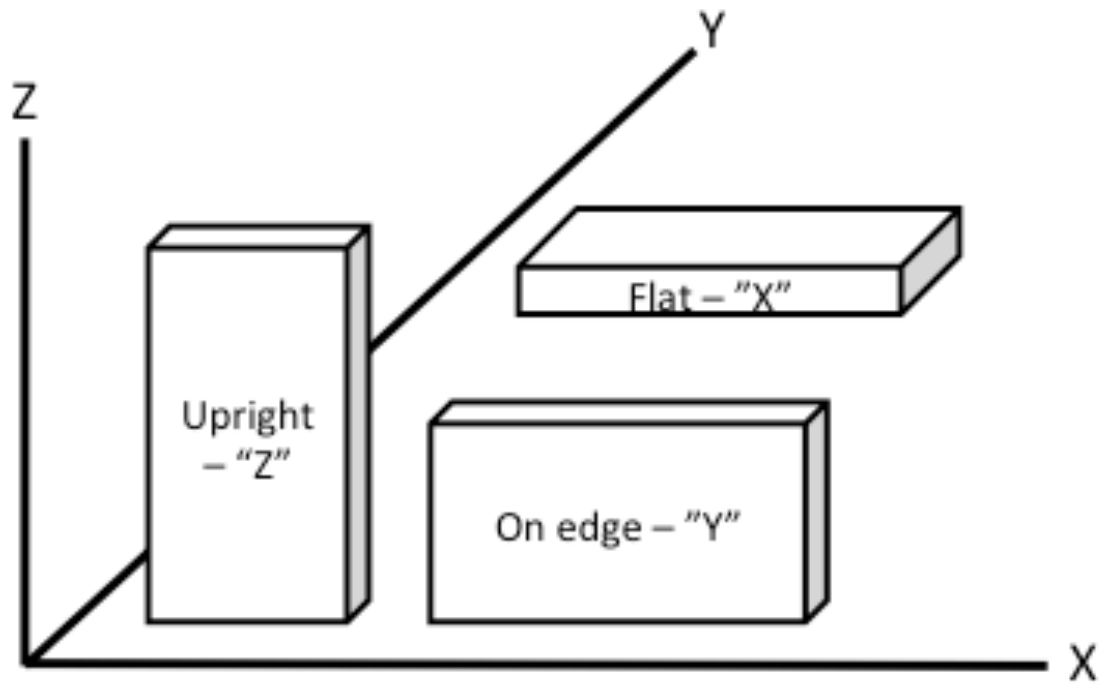


Figure B.1: Different printing orientations for AM

All resin-based material scored low in the evaluation due to their high toxicity. Moreover, the UV curing processes (or light exposure) used in SLA, DLP and PJM are not yet stable and cannot guarantee the required migration standard. In general, UV curing processes are not accepted at the manufacturer due to that reason. That said, there is an exception to be made due to recent developments in biocompatible materials that have been developed for the biomedical industry, as mentioned in the state of the art section. Chemical tests on these materials have not been conducted with the manufacturer's industry standard and hence were not included in this examination. It is possible that the new materials and processes originally designed for the biomedical industry can uphold the harsh requirements set by the manufacturer.

Visual finish

Visual finish holds two criteria. The first is the roughness of the surface in the printed element. The second is the dimensional accuracy of the part, i.e. the accuracy of the finished part compared with its CAD file and the repeatability of the process. In order to evaluate the visual finish of printed parts in the different technologies, a test using high precision scanning was conducted. This scan has just several microns in resolution and can plot a visual representation of the parts accuracy.

The results for FFF (y and x printing directions), SLS and SLA were presented and compared with an injection molded original element. Both FFF parts in both orientations presented good results, with some lacking material. SLS also showed good results, though some surplus of material was noticeable. SLA showed very good results on shafts and round parts but presented poor results on plates with a surplus of material.

Though SLA's dimensional accuracy might be low in several areas of the element, it presented the lowest surface roughness. SLA and DLP showed the lowest surface roughness and measurements were as low as 10 microns. FFF showed poor results, originating from the clear layer structure on its surface. PJM shows very poor results, though in reality its accuracy is very high. The reason for these poor results may be the remaining of support material on the parts. Due to the manual nature of the process, the repeatability of the process is low and different tests showed different results.

FFF's mechanical and chemical properties attained promising results due to the fact that these technologies use familiar materials to the manufacturer and widely used polymers while its visual finish is lacking due to the relative high layer thickness. SLS shows good results in terms of chemical properties due to the use of the technology in polyamide materials, which are considered quite safe and "consumer-friendly" by the manufacturer. However, both mechanical properties and visual finish show less promising results due to the

grainy surface of the printed parts that resulted from the powder materials the technology is based on.

All resin based technologies (SLA, DLP, PJM) scored low both on mechanical and chemical properties due to the brittleness of their materials and its high toxicity, but scored high on visual finish, mainly due to their thin layer thickness and the use of liquid-based resin which allows the smooth surfaces. Among all technologies, Zcorp has scored the lowest as a manufacturing technology due to the brittle nature of its material, the grainy surface that is a result of its powder based material, and the chemical composite of the binder used in the process.

Time, cost, volume

When benchmarking to injection molding machines with just seconds as a cycle time and significant economies of scale, it is clear that all AM technologies scored notably low. It is for that reason that their score in the evaluation remained low. Nevertheless, there was value in benchmarking the technologies to each other.

Evaluating time of production is difficult across all technologies. Many factors have to be taken into consideration such as geometries, materials, platforms, post-processing, etc. The evaluation presented here is rough determination of the time all platforms will take to manufacture a specified part. The evaluation shows that all technologies will take more than an hour for the process, while an injection molded part is manufactured in less than 20 seconds. The results of the analysis are presented in Table B.2.

The cost evaluation is made taking into consideration the price of manufacturing a part while manufacturing 10,000 pieces. This is done in order to take into account the volume of the machines and to better benchmark it to the scale of an injection molding machine. Clearly, AM machines are much slower than an injection molding machine. However FFF

prices can go as down as 0.2 euro per part, which makes it an attractive technology. SLA and PJM are significantly more expensive than FFF, while SLS is somewhat cheaper.

Table B.2: Time, cost and volume comparison for the production of parts

	FFF	SLS	SLA	PJM
Time (h)	1.5	2	2	1.2
Cost (Euro)	0.20	2.15	3.7	3.6
Volume (mm)	914 x 610 x 14	700 x 380 x 580	550 x 550 x 750	1000 × 800 × 500

Note: Zcorp technology was not evaluated in this case as its platforms are generally rather small and are not suitable for large quantities.

Multi-color and decoration

Multi-color is defined as the possibility of making a part with a single color while decoration is defined as the possibility to create color patterns on the part at the time of production. Table B.3 shows the different platforms' ability to multi-color and decorate. As can be seen, PJM and Zcorp are the only technologies that are capable of producing decorated parts with patterns. This is due to the fact that both technologies are inkjet based and color is applied to individual drops in the processes—to the glue in Zcorp and to the photopolymer in PJM. FFF is capable of multi-color since filaments can be colored in a desired color and fed to the system. Color changing is possible in the process but not to a decoration level.

It is important to note that SLS, SLA and DLP, offer some variance of colors in their materials. Black SLS powder is available, and so are different gradients of grey in SLA and

yellow/red in DLP. However, these colors cannot be changed without post-processing and hence do not qualify as multi-color or decoration.

Table B.3: The technologies ability to produce with color

Multi-color	Yes	No	No	No	Yes
Decoration	No	No	No	No	Yes
